RIGHT-LEFT ASYMMETRY OF RADIATION FROM FISSION

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Abstract

The effect of the right-left asymmetry is considered in the angular distribution of gamma quanta from fission of ^{235}U by polarised thermal neutrons, which depends on the polarisation of the neutrons with respect to the gamma—fission plane. Electric dipole radiation from fission fragments arising due to the Strutinsky—Denisov induced polarisation mechanism may give rise to such an effect. Earlier, this mechanism was shown to fit the non-statistical part observed in the γ spectrum from spontaneous fission of ^{252}Cf. The calculated value of the magnitude of the asymmetry parameter is on the level of 10^{-4}. That is in agreement with the current experimental data. A crucial experiment to give a more definite picture of the concrete mechanism would be determination of the energy of the quanta responsible for the asymmetry. Detection of the quanta with the energy of ~ 5 MeV approaching the GDR is needed in order to identify prompt gamma rays emitted at the stage of fissioning.

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1 Introduction

First results of the current experiment on search for the angular correlation in the emission of gamma quanta from fission of ^{235}U induced by thermal polarised neutrons were surprising and of great interest [1]. Polarisation of the neutron beam defines the natural quantization axis z in the laboratory frame. In ref. [1] fission fragments and gammas were detected in the orthogonal geometry, that is in the (x, y) plane, which is perpendicular to the neutron polarisation (Fig. 1). Let y be the fission axis. In [1], γ quanta were detected under the angle of ϑ_{exp} with respect to the fission axis, that is axis of y in the frame presented in Fig. 1. In the (x, y) plane, angle ϑ_{exp} is complimentary to the azimuth angle ϕ in Fig. 1:

$$\vartheta_{exp} = \frac{\pi}{2} - \phi \, . \tag{1}$$

For this reason, we will refer the results to the angle ϑ_{exp}, using (1). There is obtained an evidence that the γ emission probability depends on the right or left neutron polarisation with respect to the (x, y) plane. Furthermore, the asymmetry parameter, $R(\vartheta_{exp})$ has been obtained. That reads

$$R(\vartheta_{exp}) = \frac{N_\gamma^\uparrow(\vartheta_{exp}) - N_\gamma^\downarrow(\vartheta_{exp})}{N_\gamma^\uparrow(\vartheta_{exp}) + N_\gamma^\downarrow(\vartheta_{exp})} \, , \tag{2}$$

where $N_\gamma^\uparrow$, ($N_\gamma^\downarrow$) is the number of gammas emitted at the given angle ϑ_{exp} with respect to the fission axis when the neutron polarisation is along (right) or counter (left) the quantization axis z, respectively. The experimental values reported in [1] with 90% longitudinally polarised thermal neutrons are

$$R^{exp}(35^\circ) = (1.5 \pm 0.4) \times 10^{-4},$$

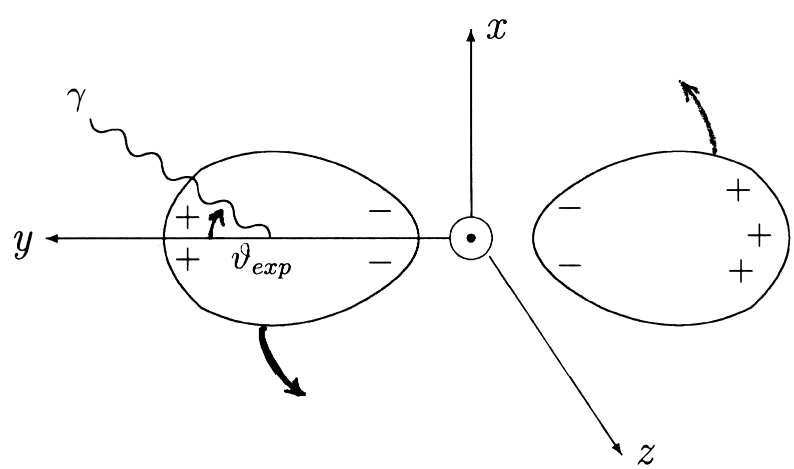

Figure 1: Scheme of study of the right-left asymmetry in radiation from fission of ^{235}U nucleus. Fission is induced by a capture of a thermal neutron (designated by an open circle at the origin) polarised along the z axis, as shown by the point in the middle. Pear-like fragments are polarised from the moment of birth. Signs '+' and '−' show redistribution of charge inside the fragments, which induces appearance of the electric dipole moments. Circular arrows show the direction of rotation of the fissile nucleus and nascent fragments caused by the polarisation of the fissile nucleus. The fragments separate in the direction of the y axis; γ quanta are registered in the (x, y) plane at the angle of ϑ_{exp} with respect to the y axis. The probability of γ emission at the given angle changes when the direction of rotation is reversed together with the neutron polarisation.

$R^{exp}(57°) = (2.3 \pm 0.4)\times 10^{-4}$, and
$R^{exp}(90°) = (-0.2 \pm 0.6)\times 10^{-4}$.

Earlier, similar effect has been found in α or another light charged particle emission in ternary fission [2]. In that case, the effect was attributed to the rotation of the fission axis after the light charged particles are ejected. Explanation of the effect needs that the alpha is emitted for the times of the order of 10^{-21} s, while the fragments did not separate on a large distance yet. Therefore, this effect is of great interest because it sheds light on the dynamics of fission at a very early stage, also clarifying the fundamentals of quantum mechanics. As distinct from α's and other strongly interacting particles, γ emission mainly occurs from fully accelerated excited fragments, past the neutron evaporation (e.g. [6]), for characteristic times of 10^{-14} – 10^{-12} s, and therefore, cannot be explained as due to the same origin.

Our present purpose is to show that, on one side, the Strutinsky—Denisov induced polarisation mechanism [3, 4] not only explains the non-statistical part of the spectrum, observed in ref. [5], but it is also strong enough, to explain the results [1]. In this case, the radiation is emitted from fragments before the neutron emission due to snapping back the nuclear surface within a time interval τ_{dis} which is determined by dissipation of the collective energy. According to [6], $\tau_{dis} \lesssim 10^{-19}$ s. Therefore, study of this effect gives invaluable information on the dynamics of this process, providing a direct confirmation of this phenomenon, which is of great interest, but very hardly observed. Previous evidence of this effect was obtained in the shaking muons emitted from the prompt fission fragments [7, 8, 9]. On the other side, at the present stage of investigation, our calculation suggests that the usual γ radiation from fragments can be expected to possess the same effect. However, even in this case, the value of the asymmetry parameter (2) depends on such a seemingly intrinsic and hardly observable property as the angular velocity of the spin rotation of the fragments, as well as dissipation of the nuclear matter, providing a unique information on these primordial features.

Generally, right-left asymmetry can also be a manifestation of violation of the space parity. Under space reflection $\mathbf{r} \to -\mathbf{r}$, spin of the neutron, as a pseudovector, remains positively directed along the new z axis, but the right coordinate system goes over the left one. Therefore, the asymmetry parameter (2) changes the sign. Whether parity violation was observed, is a question of magnitude of the effect. We return to this matter in section 6. We note that the right-left asymmetry arises because the detecting system in [1] does not distinguish between light and heavy fragments. Otherwise, an effect of a triple correlation like $(\sigma \cdot [\mathbf{p}_f \times \mathbf{k}_\gamma])$ could be observed, which is P even. Therefore, one can use this circumstance in order to clarify the mechanism of the observed phenomenon. Any effect of P violation is ruled out by mere fixing the direction of the heavy fragment and counting the angle ϑ_{exp} off this direction.

2 Physical premises

First premise is alignment of the fission fragments. Experiment shows that the fragments are formed partly aligned after scission in the plane perpendicular to the fission axis, with the average spin of $I = 7 - 8$. The effect of alignment was observed in the angular distribution of the emitted radiation [10] and conversion muons from the prompt fission fragments [11]. The spins of the fragments can be parallel or anti-parallel to each other. In the last case, their total spin is compensated by the large angular momentum of the relative motion of the fragments. At the moment of scission, the nascent fragments have a pear-like form with the noses directed

towards the point of the rupture. Wavefunction of a fragment can be presented as follows [12]:

$$\psi(\mathbf{r}) = \left(\frac{2I+1}{16\pi^2}\right)^{1/2} \begin{cases} D^I_{MK}\phi_K(\mathbf{r}') + (-1)^{I+K} D^I_{M\ -K}\phi_{-K}(\mathbf{r}') & \text{for } \pi\text{=1,} \\ i\left[D^I_{MK}\phi_K(\mathbf{r}') - (-1)^{I+K} D^I_{M\ -K}\phi_{-K}(\mathbf{r}')\right] & \text{for } \pi\text{=-1.} \end{cases} \tag{3}$$

K is thus a good quantum number. Therefore, evolution of the nuclear surface occurs under holding axial symmetry of the fragment. The symmetry axis rotates in the plane perpendicular to the spin of the fissile nucleus [13]. We choose the quantization axis z along the neutron polarisation vector, and the y axis — along the fragment direction.

The second premise comes from the shake effects brought about by the neck rupture. From mathematical view point, the rupture means break-down of the analyticity of the Hamiltonian with respect to time. The rupture starts the snapping-back of the nuclear surface [14], which goes over the oscillations of the surface smearing out in time. The lifetime of the oscillations is determined by dissipation. It can be evaluated as $\tau_{dis} \approx 10^{-19}$ s [6]. The oscillations generate electromagnetic field in space, changing with time. That causes electromagnetic processes of internal conversion and γ radiation. Thus, muon shake in muon-induced prompt fission manifests itself in muonic conversion. The calculated probability agrees with the experiment [8, 9]. In ref. [15], there was also calculated the probability of emission of γ quanta, the results are also of interest in connection with experiments [5, 16], where the non-statistical γ rays from ^{252}Cf spontaneous fission are under investigation. In the next section we revisit the results [15] in view of the present interest, make more detailed calculations and correct misprints. In section 4, we consider transformation of the angular distribution from the intrinsic to the laboratory frame. Numerical estimates are performed in section 5. We summarise the results obtained in the conclusion section, outline prospect for future research.

3 Strutinsky—Denisov mechanism of pre-neutron emission of prompt γ rays

The nuclear vibrations can be considered like the motion of a classical droplet. Write down the conventional expansion of the nuclear form in spherical harmonics

$$R(\theta,\phi) = R_0\big(1 + \beta_0 + \sum_{\lambda,\mu} \beta_{\lambda,\mu} Y_{\lambda,\mu}(\theta,\phi)\big)\ . \tag{4}$$

Main properties of the fragments can be described with the allowance for the quadrupole and octupole terms. This superposition of the even and odd harmonics leads to a pear-like form of the nucleus. It is essential that the electric dipole term in this case must be included into expansion (4) to keep the centre of mass fixed [3], the relation $\beta_1 = -0.743\beta_2\beta_3$ following from the latter condition [8, 4]. The other consequence is the appearance of the polarisation electric dipole moment in the nucleus [3]:

$$d \equiv D/e = -\kappa\beta_2\beta_3\ . \tag{5}$$

The polarizability κ in eq. (5) can be evaluated e.g. from formulae [3, 4], which agree with experiment (see also other refs. in [4]).

Considering the oscillations quasiclassically and taking into account the relaxation, put down

$$\beta_i(t) = \beta_i^{(0)} \sin\omega_i t\ \exp(-\gamma_i t/2)\ , \quad i = 2,\ 3\ . \tag{6}$$

Then the spectral density of the radiated energy is given in the classical limit [17] by the following expression:

$$d\mathcal{E}_\omega = \frac{4}{3}\left|\ddot{D}_\omega\right|^2 \frac{d\omega}{2\pi} , \tag{7}$$

where D_ω is the Fourier transform of the second derivative of $D(t)$ with respect to time. Using (5) and (6) in eq. (7), we find

$$\ddot{D}_\omega = -e\kappa\beta_2^{(0)}\beta_3^{(0)} \int_0^\infty \exp(i\omega t)\frac{d^2}{dt^2}\sin\omega_2 t \sin\omega_3 t \exp(-\gamma t/2)\; dt =$$
$$= \frac{i}{4}D_0\frac{(\omega_2+\omega_3)^2}{\omega-\omega_2-\omega_3+i\frac{\gamma}{2}} , \tag{8}$$

where $\gamma = \gamma_2 + \gamma_3$ is the total quenching, and $D_0 \equiv ed_0 = e\kappa\beta_2^{(0)}\beta_3^{(0)}$.

Supposing $\beta_2^{(0)} \approx \beta_3^{(0)} \approx 0.7$ [6], we calculate by means of formulae [4] $d_0 \approx 5$ Fm. Using then the LDM values for a representative heavy fragment ^{140}Xe, which are $\hbar\omega_2 = 2.2$ MeV, $\hbar\omega_3 = 2.8$ MeV, and evaluating γ from the lifetime $\tau_{dis} = \gamma^{-1} = 10^{-19}$ s, as it is stated previously, and finally multiplying the result by a factor of two in view of the presence of two fragments available, one immediately finds by means of eq. (7) the number of the electric dipole quanta

$$N_d = \int_0^\infty \frac{d\mathcal{E}_\omega}{\hbar\omega} \approx \frac{e^2 d_0^2\omega_0^3}{6\gamma} = 0.014 \text{ fission}^{-1} , \tag{9}$$

with $\omega_0 = \omega_2 + \omega_3 \approx 5$ MeV being the resonance frequency. We conclude that this value is in qualitative agreement with experiment [5, 16], taking into account the uncertainties connected with the value of τ_{dis}. For the value supposed, $\tau_{dis} \approx 10^{-19}$ s, the contribution of the proposed mechanism is enough to explain the experimental value.

On the other hand, we see that this contribution is proportional to τ_{dis}. Therefore, study of non-statistical γ rays from fission gives direct information about dissipation in large-amplitude collective motion represented by postrupture oscillations in the fragments.

4 Transformation to the laboratory system

Let us start from consideration of classical radiation from a polarised dipole system in the intrinsic coordinate system. Then the angular distribution will be [17]

$$\chi(\theta') = |Y_{11}(\theta', \phi')|^2 \sim \sin^2(\theta') \ . \tag{10}$$

Distribution (10) is normalised to the emission of one dipole photon from the fragment. After the separation the axis of each fragment rotates in the (x, y) plane with the angular velocity ω (Fig. 1). The angle of the symmetry axis at the moment of emission against the flight direction y will be

$$\beta(t) = \omega t \ . \tag{11}$$

Transformation from the intrinsic to the laboratory frame can be done by means of two rotations at the Euler's angles β against the axis z, and then at $\pi/2$ against the new axis y'. The spherical functions in (10) in the laboratory system can be expressed in terms of the generalised spherical Wigner functions as follows:

$$Y_{11}(\theta', \phi') = \sum_m \mathcal{D}^1_{m1}\big(\beta(t), \frac{\pi}{2}, 0\big) Y_{1m}(\theta, \phi) \ . \tag{12}$$

Inserting (12) into (10) and using formulae [18] for the $\mathcal{D}$ functions, one arrives at the angular distribution in the laboratory frame:

$$\mathrm{X}(\theta,\phi;\beta(t)) = \frac{3}{8\pi}\left[\sin^2\theta\cos^2(\phi-\beta)+\cos^2\theta\right] . \tag{13}$$

Integrating the last expression over time and taking into account the time of relaxation due to dissipation of the collective energy $\tau_{dis} \equiv 1/\gamma$, we arrive at the angular distribution in the laboratory system

$$\mathrm{X}(\theta,\phi) = \int_0^\infty \gamma e^{-\gamma t}\mathrm{X}(\theta,\phi;\beta(t))\,dt = \frac{3}{16\pi}\left[1+\cos^2\theta+\sin^2\theta\cos 2\delta\cos 2(\phi-\delta)\right] , \tag{14}$$

where

$$\cos 2\delta = \frac{\gamma}{\sqrt{\gamma^2+4\omega^2}}, \qquad \sin 2\delta = \frac{2\omega}{\sqrt{\gamma^2+4\omega^2}} . \tag{15}$$

Introducing the anisotropy parameter a, $|a| \ll 1$, we can put down instead of (14)

$$\mathrm{X}(\theta,\phi) = 1 + a\sin^2\theta\cos 2\delta\cos 2(\phi-\delta) . \tag{16}$$

Reversal of the polarisation of the incoming neutrons is equivalent to the reversal of the direction of the rotation of the fissile nucleus and the fragments. This leads to a replacement $\omega \rightarrow -\omega$, that is $\delta \rightarrow -\delta$. Therefore, we arrive by means of eq. (14) at the following expression for the asymmetry parameter:

$$R(\theta,\phi) = a\sin^2\theta\cos 2\delta\sin 2\delta\sin 2\phi = \frac{1}{2}a\sin^2\theta\sin 4\delta\sin 2\phi . \tag{17}$$

Assuming the background radiation $\mathrm{X}_b(\theta,\phi)$ to be isotropic, we can normalise it to the total number of the emitted photons per fission N_γ and arrive at the following expression:

$$\mathrm{X}_b(\theta,\phi) = N_\gamma/4\pi . \tag{18}$$

Given the number of the dipole quanta per fission N_d, and allowing for (14), one can put down an expression for the total angular distribution as follows:

$$\mathrm{X}_b(\theta,\phi)+\mathrm{X}(\theta,\phi) = \frac{1}{4\pi}N_\gamma + \frac{3}{16\pi}N_d\sin^2\theta\ \cos 2\delta\ \cos 2(\phi-\delta) . \tag{19}$$

Comparing (19) with (16), we arrive at the following expression for the anisotropy parameter a:

$$a = \frac{3}{4}\frac{N_d}{N_\gamma} . \tag{20}$$

The above expression (17) for the asymmetry parameter R is remarkable in many respects. First, it is anti-symmetric with respect to the value of $\phi = \pi/2$. The asymmetry parameter increases from zero to maximal value for $0 \leq \phi < \pi/4$. Then it diminishes again to zero, changing the sign at $\phi = \pi/2$, and becomes negative for $\pi/2 < \phi < \pi$. Then it varies in the same manner in the open angle of $\pi \leq \phi < 2\pi$. This behaviour is similar to the previously reported angular distribution which is characteristic to the ROT effect in ternary fission [2].

Second, that vanishes in the two opposite limiting cases: of very slow and very fast rotation as compared to the time of dissipation. Note that for the purpose of comparison with experiment [1], making use of (1), the angular distribution in the laboratory system (14) for $\theta = \pi/2$ can be rewritten in the form

$$\mathrm{X}(\frac{\pi}{2},\phi) = \frac{3}{16\pi}\left[1 - \cos 2\delta \cos 2(\vartheta_{exp} + \delta)\right] = \frac{3}{16\pi}\left[1 - \cos^2\delta + 2\cos^2\delta \sin^2(\vartheta_{exp} + \delta)\right] \ , \quad (21)$$

which is similar to (10), but with shifted by angle δ argument, plus an isotropic term. Correspondingly, the asymmetry parameter (17) becomes

$$R = \frac{1}{2} a \sin 4\delta \sin 2\vartheta_{exp} \ . \quad (22)$$

In the first case $\omega \ll \gamma$, the shifting angle remains small. It reads:

$$\delta \approx \frac{\omega}{\gamma} \ . \quad (23)$$

(23) has a transparent physical sense of the mean fraction of a full revolution the fragment performs before radiating. The optimal value is achieved with $\sin 4\delta = 1$, or $\delta = \pi/8 = 22.5°$. In this case,

$$R_{max} = \frac{1}{2} a \sin 2\vartheta_{exp} \ . \quad (24)$$

At first sight, similar mechanism was considered in [2] for explanation of the observed shift of the peak of the angular distribution of the ternary light particle, depending on the direction of polarisation of the incoming neutron, with rotation of the fission axis instead of rotation of the symmetry axis of a fragment. Eq. (23) gives a scale of the shift. However, the nature of the shift in our case is different. In ref. [2], the fission axis rotated at a small angle of about one degree after the emission of the ternary particle in the direction which was determined by the direction of polarisation of the fissile nucleus. Probably, that was the reason why the observed effect was called ROT effect. This effect should be considerably damped by the Coulomb interaction of all the three particles in the final state. The interaction is absent in the case of γ emission, therefore, the emitted γ's bare information on the prompt orientation of the fragments at the moment of emission. As distinct to the emission of the light charged particles, we neglect rotation of the inter-fragment axis, which is small in comparison with rotation of the fragments (see section 5).

In the second case $\omega \gg \gamma$, that is the fragments revolve many times before emission. As a result, the effect of asymmetry averages and smoothes out. This is manifested in the fact that the value of $\delta \to \frac{\pi}{4}$, and the asymmetry parameter (17), (22) vanishes together with $\sin 4\delta$. This case can be applied to the usual radiation from fragments which occurs after neutron evaporation within characteristic times of $\sim 10^{-14} - 10^{-12}$ s. For these γ quanta, the right-left effect *vanishes*, in spite of that the angular distribution of the radiation qualitatively remains similar to (10) [21].

5 The results and discussion

First, we note that the experimental data [1] exhibit the angular dependence of the asymmetry parameter similar to (22): the experimental value changes the sign when ϑ_{exp} crosses $\pi/2$.

Regarding the numerical values, simple solid-body estimation shows that with spin $I = 1$, the fragments revolve with $\omega \approx 2.1 \times 10^{19}$ s^{-1}. Therefore, with $\gamma \approx 10^{19}$ s^{-1} one obtains $\cos 2\delta \approx 0.24$.

Next task is evaluation of the anisotropy parameter a in (20). The N_d value was calculated in section 3. Let us consider the radiation background N_b. As a result of fission, deformed primary fragments are obtained with the excitation energy of around 12 MeV. The excitation energy is partly fallen down with the evaporated neutrons. Already the neutrons are emitted by the fully accelerated fragments, being kinematically shifted by the translation velocity of the fragments [6]. Only recently it was established that there is a certain fraction of prompt neutrons at the level of 10% which are emitted from the fission area before the fragments are accelerated. There is much less known about prompt gamma rays. The nonstatistical part of the spectrum [5] can be of this kind, as shown in section 3. These gamma quanta can contribute to the effect of the right-left asymmentry, as we saw in the above section. Brehmstrahlung gamma rays also can be emitted during acceleration of the fragments. Recently, brehmstrahlung was discovered in alpha decay (e.g. [19]). Angular distribution of the brehmstrahlung quanta would be the same as that in (10), and therefore, that would be accompanied by a related right-left effect due to rotation of the inter-fragment axis. However, fission fragments are much heavier than alphas, and moreover, the dipole moment of a pair of fragments is close to zero because of near constancy of the fragment Z/A ratio. For these reasons, one should not expect any essential manifestation of the brehmstrahlung. Estimates can be done similar to those for the induced electric dipole radiation which were made in section 4. Let Z_1, A_1, Z_2 and A_2 be the atomic and mass numbers of the heavy and light fragments, respectively, and $Z = Z_1 + Z_2$, $A = A_1 + A_2$ are the atomic and mass numbers of the fissile nucleus, respectively. The energy radiated during time dt reads as follows [17]:

$$dI_\gamma/dt = \frac{2}{3}\ddot{d}^{\,2} \; . \tag{25}$$

In the center of mass system of the fragments the electric dipole moment is

$$d/e = (Z_1A_2 - Z_2A_1)R/A = \left[(Z_1^0 + q)A_2 - (Z_2^0 - q)A_1\right] R/A = Rq \; , \tag{26}$$

where $Z_i^0 = A_i(Z/A)$, $i = 1, 2$, and R is the interfragment distance. Therefore, effective charge of the fragments for the brehmstrahlung is

$$q = Z_i - Z_i^0 \; , \qquad |q| \ll Z_i \; . \tag{27}$$

On the other hand, from the Newton's law we get for the acceleration of the fragments

$$\ddot{R} \equiv \ddot{d}/qe = \nu/MR^2 \; , \tag{28}$$

with $\nu = Z_1Z_2e^2$, and M being the reduced mass of the fragments. Substituting (28) into (25) and integrating over all the fission trajectory from the initial point R_0, which we will fix by assuming zero total kinetic energy of the fragments at this point, to infinity, one gets the expression for the radiated energy:

$$I_\gamma = (qe)^2 \frac{2\sqrt{2}\sqrt{E - \nu x}}{45\nu M^{3/2}} \left[3(E - \nu x)^2 - 10E(E - \nu x) + 15E^2\right]\Big|_{1/R_0}^{0} = \frac{16\sqrt{2}}{45} \frac{q^2E^{5/2}}{Z_1Z_2M^{3/2}} \; , \tag{29}$$

with E being the total kinetic energy of the separated fragments.

For a given mass number, fragment distribution over Z is close to the Gauss distribution with the dispersion $\sigma \approx 2$. With this characteristic value of q and mean total kinetic energy $E = 160$ MeV, by means of eq. (29) one finds

$$I_\gamma = 2.0 \cdot 10^{-5} \text{ MeV} . \tag{30}$$

An estimate for the number of brehmstrahlung quanta with the energy within a domain of 100 keV to 5 MeV

$$10^{-5} \text{ fission}^{-1} \leq N_\gamma \leq 2 \cdot 10^{-4} \text{ fission}^{-1} \tag{31}$$

follows (30). As expected, these values are too low to produce a noticeable effect of right-left asymmetry.

According to the experimental spectrum [20], average number of quanta emitted per fission is $N_\gamma \approx 8$ fission^{-1}. Assuming the isotropic angular distribution of these quanta, and given the total probability of the electric dipole quanta of (9) with the angular distribution (10), we can estimate the parameter a to be $a \approx \frac{3}{4} \cdot 0.014/\ 8 \approx 0.0013$. By means of (22) we then get an estimation of the asymmetry parameter $R(\vartheta_{exp}) = 2.8 \times 10^{-4}$ for the angles of $\vartheta_{exp} = 35°$ and 57°, and $R(90°) = 0$. These values are close to the experimental values [1] for these angles cited in Introduction. Note that for a slower rotation of the fragments, the value of $\cos 2\delta$ could be higher. The maximal value of the asymmetry parameter (24) could be by a factor of 2 higher.

Up to now, however, we did not discuss the energy dependence of the effect. In the above example, we retained only the resonant term in (9), corresponding to emission of the quanta with the total energy of approximately 5 MeV. From the experimental spectrum from fission [20] one can conclude that effect-to-background ratio would be much better in this domain. Thus, there is only ~ 0.3 quanta per fission with the energy $E_\gamma > 2.5$ MeV. With this background value, one arrives at the asymmetry parameter $a = \frac{3}{4} \cdot 0.014/0.3 = 0.035$, and the corresponding right-left effect R at the level of 10^{-2}.

6 Conclusion

1. It is shown that the observed effect of right-left asymmetry in gamma radiation can be explained as due to emission from rotating fragments. The rotation is due to the primary polarisation of the fissile nucleus whose rotational moment partly transfers to the fragments after the scission.

2. According to (9), this effect is predicted for the γ quanta of sufficiently high energy, approaching the giant dipole resonance. This is in accordance with the time scale, which is of the order of 10^{-19} s. For smaller energies, the emission probability is lower by orders of magnitude. The radiative lifetime is less than one period of rotation of a fragment. Therefore, study of the effect for such hard gammas presents an information about the process of fission at this early stage.

3. For further understanding, the energy dependence of the effect is highly needed to be measured in experiment. In the above example, we retained only the resonant term corresponding to emission of the quanta with the total energy of approximately 5 MeV. We neglected the other resonant term with the difference energy in (9) $\omega_{dif} = \omega_3 - \omega_2 = 0.6$ MeV, because in this case the expected emission probability is by three orders of magnitude less, being proportional to the cube of the energy. An important conclusion for experiment follows this result. In order to study early stages of fission, one should detect hard γ quanta with the energy in the region

of giant dipole resonance (though reduced considerably by elongation of the fissile nucleus), as in refs. [5, 20].

4. The mechanism discussed above has nothing in common with parity nonconservation. Manifestation of the latter in fission generally starts at the level of 10^{-4}. Violation of conservation of parity remains the next candidate to be at least partly responsible for the observed result. Therefore, more detailed experiments should shed light on the origin of the effect. However, equally in this case, the γ's must be emitted within the time interval of about $\sim 2\pi/\omega \sim 10^{-19}$ s, as shown in section 4. Moreover, abstracting from the background, one can conclude from (14) that the right-left effect by itself in prompt γ rays would be of the order of 10^{-1}, which magnitude is much higher than that which could be expected from the parity violation effects.

5. Estimates are made of the brehmstrahlung energy from fragments. The estimates show that the brehmstrahlung in fission is very weak, in contrast with that in α decay.

6. Study of the above effect gives information on the dynamics of fission at the stage of snapping back the nuclear surface of the born fragments. Hence that is a direct confirmation of this phenomenon [14], which is of great interest, but very hardly observed. Previous evidence of this effect was obtained in the shaking muons emitted from the prompt fission fragments [7, 8, 9].

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References

[1] G.V.Danilyan. Invited talk at the XLI PNPI Winter School on the Nuclear and Particle Physics, St. Petersburg, Repino, 19 – 24 February 2007; ISINN—2008, June 11-14, 2008, Dubna, Russia..

[2] F.Goennenwein, M.Mutterer, A.Gagarski, I.Guseva, G. Petrov, et al., Phys. Lett. **B652** (2007) 13.

[3] V.M.Strutinsky. At. Energ., 1956, No. 4, p. 150. (*In Russian.*)

[4] V.Yu.Denisov. Yad. Fiz. **55** (1992) 2647; **49** (1989) 644.

[5] H. van der Ploeg et al. Phys. Rev. Lett. **68** (1992) 3145; KVI annual report, 1991, p. 17.

[6] Yu. P. Gangrsky, B. N. Markov, V. P. Perelygin. Registratsia i sipektrometria oskolkov delenia. Moscow: Energoizdat, 1992 (in Russian) (Registration and Spectrometry of the fission fragments)

[7] F.F.Karpeshin. Fission in Muonic Atoms and Resonance Conversion. St.-Petersburg: "Nauka", 2006. (*In Russian.*)

[8] F.F.Karpeshin. Z. Phys. A**344** (1992) 55; Yad. Fiz. **55** (1992) 2893.

[9] G. Ye.Belovitsky et al. In: "Fiftieth Anniversary or Nuclear Fission", Proc. Intern. Conf., St. Petersburg, 1989. V. 1, P. 313.

[10] Skarsvag K. Phys. Rev. **C22** (1980) 638.

[11] F.F.Karpeshin. Nucl. Phys. **A617** (1997) 211.

[12] A.Bohr and B.Mottelson. Nuclear Structure. Vol. II. W.A.Benjamin, Inc. New York, Amsterdam, 1974.

[13] F.F.Karpeshin. Yad. Fiz. **40** (1984) 643. (*Engl. transl.* Sov. J. Nucl. Phys. (USA), *40* (1984) 412.)

[14] J. Halpern. Ann. Rev. Nucl. Sci. **21** (1971) 245.

[15] F.F.Karpeshin. In: International School-Seminar on Heavy Ion Physics. Ed.: Yu.Ts.Oganessian, Yu.E.Penionzhkevich and R.Kalpakchieva. Dubna: 1993. Vol. 1, P. 294; arXiv:0710.1743v1.

[16] A.Wiswesser e.a. GSI annual report, 1991, P. 79.

[17] L.D.Landau, E.M. Lifshitz. Teoria Polya, Moscow: Nauka, 1973. (*In Russian*) (Theory of Field)

[18] A.R.Edmonds. Angular moments in Quantum Mechanics. CERN 55-26, 1955.

[19] D.M.Brink. In: Fission Dynamics of Atomic Clusters and Nuclei. Ed. by J. da Providencia, D.M.Brink, F.Karpechine and F.B.Malik. World Scientific, New Jersey— London—Singapore—Hong Kong, 2001, P. 248.

[20] R.W. Peelle, F.S. Meienshein. Phys. Rev. **C3** (1971) 373.

[21] V.M.Strutinsky. ZhETP, **38** (1959) 861.